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LOW DROP-OUT VOLTAGE REGULATOR AND METHOD**Field of the Invention**

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This invention relates to voltage regulators, and particularly to low drop-out (LDO) voltage regulators.

10 Background of the Invention

A low drop-out voltage regulator is a regulator circuit that provides a well-specified and stable DC voltage (whose input-to-output voltage difference is typically 15 low). The operation of the circuit is based on feeding back an amplified error signal which is used to control output current flow of a pass device (such as a power transistor) driving a load. The drop-out voltage is the value of the input/output differential voltage where 20 regulation is lost.

The low drop-out nature of the regulator makes it appropriate (over other types of regulators such as dc-dc converters and switching regulators) for use in many 25 applications such as automotive, portable, and industrial applications. In the automotive industry, the low drop-out voltage is necessary during cold-crank conditions where an automobile's battery voltage can be below 6V. Increasing demand for LDO voltage regulators is also 30 apparent in mobile battery operated products (such as cellular phones, pagers, camera recorders and laptop computers), where the LDO voltage regulator typically

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needs to regulate under low voltage conditions with a reduced voltage drop.

- A typical, known LDO voltage regulator uses a
5 differential transistor pair, an intermediate stage transistor, and a pass device coupled to a large (external) bypass capacitor. These elements constitute a DC regulation loop which provides voltage regulation.
- 10 For the (LDO) low drop-out voltage, generally in the closest known technology the load capacitor forms the dominant pole, and due to this the capacitor has to be specified with a minimum and maximum serial resistance. As the load is part of the regulation loop, it is
15 possible for instability to be caused by such indeterminate factors as parasitic capacitance.

However, this approach has the disadvantage(s) that, since the load is part of the regulation loop:

- 20 • the LDO regulator typically needs an external capacitor in order to ensure stability.
• the loop DC gain changes versus the load resistance and the capacitor value
• the capacitor has to be specified with a minimum and
25 maximum ESR (Equivalent Serial resistor)

A need therefore exists for a low drop-out voltage regulator in wherein the abovementioned disadvantage(s) may be alleviated.

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Statement of Invention

In accordance with the present invention there is provided a low drop-out voltage regulator and a method 5 for low drop-out voltage regulation as claimed in claim 1 and claim 12 respectively.

Brief Description of the Drawings

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One low drop-out voltage regulator, in which the load capacitor is not used "for dominant pole", incorporating the present invention will now be described, by way of example only, with reference to the accompanying 15 drawings, in which:

FIG. 1 shows a schematic circuit diagram of a conventional LDO voltage regulator in which the output is high impedance and the load (and hence the 20 load capacitor) are part of the voltage regulation loop;

FIG. 2 is a graph illustrating pole tracking behaviour of the circuit of FIG. 1;

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FIG. 3 shows a schematic circuit diagram of an LDO voltage regulator incorporating the present invention;

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FIG. 4 is a graph illustrating operational behaviour of a main loop of the circuit FIG. 3;

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FIG. 5 is a graph illustrating operational behaviour of an impedance follower arrangement of the circuit portion of FIG. 3;

5 FIG. 6 shows a block-schematic representation of the LDO voltage regulator of FIG. 3;

FIG. 7 is a graph illustrating operational behaviour of the circuit of FIG. 3.

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Description of Preferred Embodiment

Referring firstly to FIG. 1, a prior-art, conventional
15 LDO voltage regulator (100) uses a differential transistor pair arrangement (T1-T4), an intermediate stage transistor arrangement (T5-T6), and a pass device (T7) coupled to a large (external) bypass capacitor (CL) having an equivalent series resistance (ESR). The
20 differential transistor pair arrangement (T1-T4) receives a BandGap reference voltage (Vbg), and is supplied with a supply voltage (VSupply) through a voltage source (VS). These elements constitute a DC regulation loop which provides low drop-out voltage regulation of an Output
25 Voltage applied to the external bypass/load capacitor (CL).

The bypass/output PMOS device (T7) allows a low drop-out voltage to be obtained between Supply and Output voltage,
30 but as the output is made with the drain of the PMOS device (T7), the output is high impedance and the load (and hence the load capacitor) are part of the loop.

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Since the load capacitor (CL) is used in the main loop of the regulator, the external capacitor (CL) will affect the stability of the loop due purely to its capacitance or too high a value of ESR.

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- Referring now also to FIG. 2, the plot of gain (A) of the voltage regulation loop against frequency (f) shows a dominant pole (F_{pout}) created by the output capacitor (CL), a zero (Z_{esr}) created by the ESR of the output capacitor (CL), a further sub-dominant pole (F_{pdiff}) created by the differential pair arrangement (T1-T4) and a further sub-dominant pole (F_{pin}) created by the intermediate stage (T5-T6). It will be understood that the use in the intermediate stage of device T5 alone produces the plot shown in full line in FIG. 2, and that the use additionally of device T6 allows pole tracking of the poles F_{pout} and F_{pin} as shown by the arrowed dashed lines in the figure.
- 20 Referring now to FIG. 3, an improved LDO voltage regulator 300 has a differential amplifier B, whose inputs are respectively connected via a resistive divider r_1 , r_2 and via a source of reference voltage v_{ref} to an output node. The output of the differential amplifier B is connected to the base of a bipolar PNP transistor Q1, whose emitter is connected to the output node, and whose collector is connected via a source of DC current I_{dc} to a ground rail. A cascaded bipolar NPN transistor Q2 has its emitter connected to the collector of transistor Q1, and has its base connected via a source of bias voltage V_b to the ground rail. The collector of the transistor Q2 is connected via a resistor r_g to a rail of supply
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- voltage V_{bat} . A PMOS transistor Q3 has its current electrodes connected between the supply rail and the output node, and has its control electrode connected to the collector of transistor Q2. Although the transistor
- 5 Q3 is shown as an MOS device, it will be understood that a bipolar P-type transistor, i.e., a PNP device could alternatively be used. A capacitor C_g is connected between the output node and the collector of transistor Q2. The output node is connected to a load represented
- 10 by a load capacitor c_L , a load resistor r_L and a resistor r_s . It will be understood that the transistor Q3 is connected in 'common source' configuration, and has a non-unity open-loop gain which in closed-loop mode becomes a unity gain since the output V_{out} is connected
- 15 with the emitter of transistor Q1. In use of the LDO voltage regulator 300, an input voltage v_{in} is developed at the output of the differential amplifier B, an input current i_{in} flows into the emitter of the transistor Q1, a current i_{rg} flows across the resistor r_g , and an input
- 20 current i_{out} flows from the transistor Q3 to the output node. It will be understood that the transistor Q1 has a transconductance gm_1 and the transistor Q3 has a transconductance gm_2 .
- 25 The LDO voltage regulator circuit 300 can be considered in two parts:
- a 'main loop' 310 comprising the resistive divider r_1 , r_2 and the differential amplifier B; and
 - a 'follower impedance' 320 comprising the remaining
- 30 components of FIG. 3 (as will be explained in more detail below, the 'follower impedance' provides an

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impedance adaptor providing a high input impedance and a low output impedance and a follower amplifier having closed-loop unity gain).

- 5 Referring now also to FIG. 4, the open-loop operational behaviour of the 'main loop' 310, plotted as gain versus pulsation (frequency), shows that with increasing frequency the gain has a maximum value of BK (where B is the gain of the differential amplifier B , and $K = \frac{r_1}{r_2 + r_1}$)
- 10 up to a dominant pole at frequency ω_{pd} , (thereafter decreasing and crossing zero at a frequency ω_{0d}). It can be shown that the ratio of v_{in} and v_{out} , the open-loop gain B_{OL} , is given by:

$$\frac{v_{in}}{v_{out}} = B_{OL} = B.K \frac{1}{1 + j\left(\frac{\omega}{\omega_{pd}}\right)}$$

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- Referring now also to FIG. 5, the operational behaviour of the 'follower impedance' 320, plotted as open-loop gain A_{OL} versus pulsation (frequency), shows that with increasing frequency the gain begins at a maximum value A_{max} , and decreases (starting at a pole at a frequency ω_p , and ending at a pole at a frequency ω_2 , and crosses a zero value at a frequency ω_0). It will be understood that the closed-loop gain A_{CL} (shown in dashed line) of the 'follower impedance' 320 begins at a zero value up to the frequency ω_0 , and thereafter becomes the same as the open-loop gain A_{OL} , decreasing to the minimum value A_{min} at the frequency ω_2 . It can be shown that the open-loop gain A_{OL} is given by:

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$$A_{OL} = (G_i + 1) g m_1 r_L \left(\frac{1 + j \frac{\omega}{\omega_2}}{1 + j \frac{\omega}{\omega_p}} \right)$$

where $G_i = \frac{i_{out}}{i_{rg}}$, $\omega_p = \frac{1}{(r_L + r_s)c_L}$, $\omega_2 = \frac{1}{r_s c_L}$, $\omega_o = \frac{1}{\frac{r_e}{(G_i + 1)} c_L}$,

$A_{max} = g m_1 (G_i + 1) r_L$, and at high frequencies $A_{min} = \frac{r_s}{r_e} (G_i + 1)$,

and that the closed loop gain is given by:

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$$A_{CL} = \frac{1}{1 + j \left(\frac{r_e c_L \omega}{G_i + 1} \right)}$$

where r_e , the dynamic impedance of the transistor Q1, is equal to $\frac{1}{g m_1}$.

It will be noted that the load impedance (r_L) appears in
10 the open loop gain (A_{OL}), but not in the closed-loop gain
(A_{CL}) where $V_{out} = V_{in}$. It will be understood that this
results in DC output current not changing the closed-loop
gain.

15 It will therefore be understood that in the LDO voltage
regulator 300 transistor Q1 creates a low output
impedance with an emitter follower, and the load
capacitance is divided by the current gain of the second
stage. Therefore, the pole created by the load
20 capacitance is high, because RC is low (R low due to the
emitter follower, C low due to the output capacitor's
value being divided by, for example, 1000). The dominant
pole is given by the amplifier compensation (main loop

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with amplifier B) and not dependant on the load (up to a load of, for example, $10\mu F$).

Referring now also to FIG. 6, it will be appreciated that
5 in a block diagrammatic representation the LDO voltage regulator 300 has a main loop 310 which contributes a dominant pole T_1 , an output loop provided by the 'follower impedance' 320 which contributes sub-dominant pole T_2 , and internal DC feedback 330. It will be
10 understood that in the gains of the blocks 310 and 320 of FIG. 6, the symbol s represents the Laplace operator.

Referring now also to FIG. 7, the cumulative effect of the poles T_1 and T_2 can be seen in the overall gain A of
15 the regulation control loop in the LDO voltage regulator 300. As can be seen, the internal pole T_1 provided by the amplifier B is a dominant, ultra-low pole. It can also be seen that no dominant pole is created by the output bypass capacitor C_L , allowing strong stability for
20 any capacitor used for this function. The pole created by C_L ($1/T_2$) appears when the gain is less than 1 and not before. Tests have shown that the LDO voltage regulator 300 exhibits good stability and low variation for a range of values of output capacitance.

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It will be understood that the low drop-out voltage regulator where the load capacitor is not used "for dominant pole" described above provides the following advantages:

30 1. The output capacitor can be dramatically reduced in size, or may be removed (a low dominant pole, provided by the main loop with amplifier B, allows

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the LDO voltage regulator 300 to work with a 0nF output capacitor).

2. Internal power consumption can be reduced (for example, 100 μ A may be enough to drive the full output current, up to 100mA current limit), providing improved regulator efficiency.
- 5 3. Low output impedance is produced (the DC output resistance is very low, less than 10 m Ω , for example).
- 10 4. The external capacitor can have a ESR (equivalent serial resistor) of zero.

It will be understood that the low voltage drop-out regulator 300 will typically be fabricated in an integrated circuit (not shown).

15 It will be further appreciated that other alternatives to the embodiment of the invention described above will be apparent to a person of ordinary skill in the art. For example, the PMOS transistor Q3 may be cascoded to increase the output impedance in order to improve line transient performance of the LDO regulator.